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Assessment of conformance and interoperability testing methods used for construction industry product models ☆

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ABSTRACT

This paper presents a review and assessment of conformance and interoperability testing methods for product data models used in the construction industry. Conformance testing methodologies, with varying degrees of rigor, have been developed and applied to ensure interoperability across product modeling software applications in other engineering and industry domains, such as, engineering and manufacturing of automotive and aerospace products. Current conformance testing and evaluation of interoperability for construction industry product modeling software do not necessarily apply those same principles and are usually done on an ad-hoc basis. Key principles are identified for improved methods and metrics for developing conformance and interoperability testing capabilities for the construction industry.

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1. Introduction

Over the past 30 years, most sectors of the construction industry have adopted the use of computer-aided design (CAD) and computer-aided engineering (CAE) applications. This started with industrial plant design and structural engineering and moved to additional disciplines, work processes and building types. As each sector has expanded its portfolio of software applications and the use of digital information to drive work processes, effective information management and reliable product data exchange has become critical. With the recent adoption by the architecture, engineering and construction industry of the benefits and challenges of using building information modeling (BIM), the general building industry has also recognized the importance of interoperability among the various software applications used over the life cycle of a construction project, from preliminary design through construction, commissioning, and handover for operations and maintenance.

Industry sectors which have been leaders in the successful use and integration of CAD/CAE across complex enterprises, for example the aerospace and automotive industries, invested in:

- developing product data exchange (PDE) specifications for their important information flows;
- validating these draft PDE specifications, and
- defining conformance and interoperability testing for ensuring that software implementations comply with the PDE specification and that interoperability among software applications can be achieved.

However, this overall strategy has not yet gained traction in the construction industry. The construction industry has efforts developing PDE specifications such as the Industry Foundation Classes (IFC) [1] and the CIMsteel Integration Standards (CIS/2) [2,3], but these efforts have not included robust validation as part of developing these PDE specifications and have not developed test suites or tools to enable rigorous conformance testing for software applications. The extra costs to develop the conformance test suites, to establish the neutral testing environment and to perform the testing across multiple software implementations have been impediments to achieving the needed level of conformance testing capabilities. Additionally, there is also a lack of industry consensus on methods and metrics for conformance, interoperability, and validation testing and how these should be included in the development and public review of draft PDE specifications such as the proposed National Building Information Modeling Standard [4].

Fortunately, industry leaders and government agencies now recognize the importance of addressing this situation. There are numerous reports which have documented the imperative to solve this problem. Industry assessments continually report disappointment in the lack of progress in achieving interoperability among software tools [5,6]. The recent National Research Council report

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"Advancing the Competitiveness and Efficiency of the U.S. Construction Industry" reinforced conclusions from earlier reports [7] that the lack of interoperability is a major source of construction industry waste and inefficiency. This paper provides a baseline assessment of the current conformance testing and evaluation of interoperability for construction industry product modeling software and defines key principles for developing conformance and interoperability testing capabilities for the construction industry. Section 2 defines conformance and interoperability testing as it applies to product data models used in the construction industry. Sections 3 and 4 provide details of how interoperability and conformance testing has been performed for IFC, CIS/2, and other product data models in a variety of projects and programs. Sections 5 and 6 provide an analysis of the testing projects and programs and recommendations for improvements to conformance and interoperability testing.

2. Definition of conformance and interoperability testing

Many different industries and domains that require the testing of software and hardware systems have developed similar definitions of conformance testing and interoperability testing. For example, the ISO/IEC (International Standards Organization/International Electrotechnical Commission) Guide 2 [8] provides the following definitions for conformance testing and related terms:

- Conformance testing — a way of verifying implementations of a specification to determine whether or not deviations from the specification exist. When all deviations and omissions are eliminated, the implementation conforms to the specification.
- Test suite — a combination of test software, procedures, and documentation, is used to check an implementation for conformance to a specification.
- Test software — a set of test files, programs, or scripts that check each requirement of the specification to determine whether the results produced by the implementation match the expected results as defined by the specification.
- Test procedures — the administrative and technical process for testing an implementation. The test documentation describes how the testing is to be done and the directions for the tester to follow with sufficient detail so that testing of an implementation can be repeated with no change in the test results.

Conformance testing of telecommunications equipment is defined by the European Telecommunications Standards Institute (ETSI) as the act of determining to what extent a single implementation conforms to the individual requirements of its base standard. ETSI also defines interoperability testing as the act of determining if end-to-end functionality between at least two communicating systems is as required by those base systems' standards [9].

The Software and Systems Division at the National Institute of Standards and Technology (NIST) has a long history of developing conformance test suites, methods, and frameworks for a wide variety of software systems including the Document Object Model (DOM), the Virtual Reality Modeling Language (VRML), and the Electronic Business Extensible Markup Language (ebXML) [10]. Testing, as defined by NIST, that is related to these software systems uses similar definitions of conformance testing and test suites. It also defines other terms related to testing, such as:

- Validation — the process necessary to perform conformance testing in accordance with a prescribed procedure and official test suite
- Certification — acknowledgement that a validation was completed and the criteria established for issuing certificates was met

While none of the definitions above were developed to relate specifically to the conformance and interoperability testing of PDE specifications such as IFC and CIS/2, the definitions from above provide key principles that can be applied. Kindrick et al. [11] provide key principles of how to improve conformance and interoperability testing specifically for STEP (ISO 10303, also known as Standard for the Exchange of Product Model Data) [12]. This guidance can be applied to IFC and CIS/2. Many key principles and observations about conformance and interoperability testing are given, such as, conformance testing provides the basis for determining interoperability between systems. Conformance testing can detect interoperability problems early in the development of a software product. The development of test suites and testing tools, and performing the tests can be costly and time consuming; therefore they need to be constructed in such a way to maximize the benefits and cost-effectiveness of the testing.

A software system that is shown to pass conformance testing does not guarantee that it can reliably interoperate with other systems that have also passed the same conformance testing for the data exchange specification. However, non-conformant systems will be less likely to interoperate. While conformance testing is focused on the specific requirements of the standard, interoperability testing examines characteristics related to how information is exchanged between systems. Without conformance testing, successful interoperability testing results in satisfying the requirements of point-to-point information exchange, i.e., between only two systems with no guarantee that either can interoperate with a third system [11].

For implementations of data exchange standards, conformance testing can either be *preprocessor* or *postprocessor* testing. In preprocessor testing, input specifications are used to model an object in the software system that is being tested and then the model is exported in an exchange format such as CIS/2 or IFC. The input specifications for the object to be modeled can include dimensions, type of geometry representation, materials, and relationships between other objects in the model.

For preprocessor testing, the resulting exchange format file is analyzed for syntax, structure, and semantics [11,13]. The analysis of the syntax of the exchange format file looks at the 'grammar', i.e., is the correct types of data elements and values used: strings, integers, real values, enumerations, etc. Structure analysis looks at the values, entities, and relationship between them. For example, is the thickness of the web of I-beam less than the width of the I-beam or are materials assigned to objects? The syntax and structure of a file can be tested with several free and commercial STEP file checkers. Testing the semantics of the file involves determining if the information in the file is accurate with respect to the input specifications of the model.

Postprocessor testing involves importing the exchange format file into a software system and analyzing the resulting model. Semantic analysis also applies to postprocessor testing in that the resulting model is analyzed with respect to the input exchange file. The analysis of the resulting model is much harder than syntax or structure analysis because there are no automated tools to do it. Postprocessor testing usually involves a visual inspection of the resulting model and a check that attributes match similar attributes in the original model that generated the exchange format file. Typically, postprocessor testing would be done by inspecting the CAD model after an IFC file was imported. The lack of automated tools to do the inspection limits the criteria that can be used to verify that the resulting model is correct. The testing is usually limited to a user inspecting attributes of individual building elements.

Interoperability testing starts with the input specification for an object (e.g. a beam, frame, room, or building) which is modeled in a preprocessor software system. An exchange file is then exported from the preprocessor and imported to a postprocessing system. The resulting model in the postprocessing system is analyzed for similarities and differences between it and the model in the originating preprocessor system and the input specifications. Conformance testing should also be performed on the exchange file exported from the preprocessing system to ensure better interoperability.

With either conformance or interoperability testing, verdict criteria are used to test whether the software system being tested has passed either type of test. The verdict criteria for conformance testing exchange files are whether the file conforms to the syntax, structure, and semantics of the PDE and input specifications of the object being modeled. The verdict criteria for interoperability testing usually include the visual representation of the model in the receiving postprocessing system and an inspection of the attributes of the model.

Analysis of the coverage of the requirements of a PDE standard by a set of test files is also important for understanding the utility of the testing results [14]. Relating coverage analysis to the IFC schema, it can indicate which parts of the schema or specific subset is covered by a set of test files and conversely which parts are not. It can also help guide generation of IFC test files to ensure a required level of coverage and to help identify redundant test files that do not increase coverage. Of course measuring the coverage of a single test file against the entire IFC schema is not very useful. However, measuring the coverage of a set of test files against a subset of the schema such as different aspects of walls with windows and doors could provide useful information. For example, a set of IFC models of walls with windows and doors could be measured for different combinations of information concepts, such as geometry, material composition, and other attributes. Coverage analysis would indicate which information concepts are and are not contained in the set of files. This can lead to the development of a more optimal set of test files, for those information concepts, that can be used for conformance and interoperability testing.

3. Summary of IFC-related interoperability projects

The following is a summary of many IFC-related interoperability testing projects that were compiled through a literature review and from the author's participation in and knowledge of the testing projects. The largest testing effort is the IFC certification process which is used to certify that a software application has met the requirements of the certification tests. Of the other projects that are summarized, some test only interoperability with IFC files while others include other aspects of interoperability and conformance testing. In general they do not follow the procedures and methods for doing conformance and interoperability testing described in the previous section.

The summary of the testing projects includes the characteristics of the original CAD or IFC file used; how the IFC files were exchanged; the criteria used for evaluating the exchange or resulting CAD model; and how the results are reported. Some of the results of the interoperability testing are presented and others can be found in the references related to each project.

All of the tests that are summarized contain some characteristics of the benchmark test workflow diagram shown in Fig. 1.

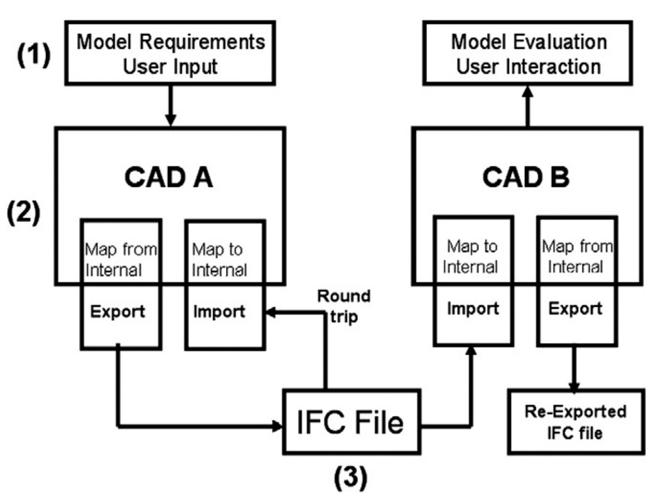

Fig. 1. Benchmark test workflow diagram.

The general workflow is that a model is generated in application CAD A and then exported to an IFC file, which is then imported to application CAD B. The assumption is that CAD A and CAD B are similar types of design systems, such as, architectural or structural. All the summarized interoperability benchmark tests have different starting points in the workflow diagram, including:

(1) the requirements for the CAD model and how it should be modeled by a user,
(2) an existing CAD model (CAD A), or
(3) an existing IFC file.

The workflows of the tests are not all from a single CAD system to only one other CAD system as shown in the diagram. Often multiple originating or receiving CAD applications are used. Some workflows start with the definition of a single model that is created in many CAD applications from which IFC files are exported and imported to a single CAD application. Other workflows involve a model from a single CAD application that is exported to an IFC file and imported to many CAD applications.

Some workflows also “re-export” an IFC file after the original IFC file has been imported to a CAD application. A “roundtrip” testing workflow takes the IFC file exported from a CAD application and “re-imports” it back into the original CAD application and then, without modifying the CAD model, a second IFC is exported. The purpose of these workflows is to be able to compare the original IFC file to the second exported IFC file.

An important aspect of the workflow diagram is that there is a mapping to and from the internal representation of information in a CAD application when the CAD model is imported or exported as an IFC file. The IFC schema was never intended to be a complete neutral representation of all information in CAD applications and in almost all cases there is not a direct one-to-one mapping between the internal CAD representation and external IFC file representation. Depending on the type of test, the information about the model will be mapped multiple times. A simple interoperability test between two CAD applications involves mapping information twice when the IFC file is first exported and then imported to the receiving CAD application.

Applying the definitions, from the previous section, of conformance, interoperability, preprocessor, and postprocessor testing to the workflow diagram, there are two conformance testing scenarios and a single interoperability testing scenario. The first conformance test would start with model requirements and then analyze the resulting IFC file exported from CAD A and the second would start with an IFC file and analyze the resulting model in CAD B. The interoperability test would start with model requirements that are modeled in CAD A and export an IFC file from CAD A that is imported to CAD B where the resulting CAD model is analyzed. For either type of test, the analysis of the resulting IFC file is more straightforward than analyzing the resulting CAD model. Various software tools can be used to inspect and visualize the information in an IFC file. Software tools such as EDM Supervisor [15], STEP Tools [16], and Express Engine [17] can be used for preprocessor testing of syntax and structure. Visual inspection can be done with any of the many IFC viewers that are available. However, the analysis of the resulting CAD model is usually only a manual inspection of the CAD model geometry and attributes of building elements. For anything other than very simple CAD models, manual inspection is not practical.

The application of evaluation criteria to measure conformance or interoperability of the IFC files or CAD models can take place at different points in the benchmark test workflow diagram, such as the model in CAD A; the exported IFC file and comparison to the original CAD model; the resulting model in CAD B and a comparison to the model in CAD A; the comparison of the original IFC file with the re-exported IFC file or the second IFC file in the roundtripped workflow.

Some of the testing scenarios shown in the benchmark test workflow diagram are not necessarily representative of typical workflows. The “roundtripping” and “re-export” type of tests do not reflect normal usage of IFC files or of the CAD model, nor is it an objective of the IFC certification process described below. They also do not conform to the definition of conformance or interoperability testing. They only serve the purpose of being able to compare and evaluate IFC files before and after they are exported from a CAD application. There are some evaluation criteria that can be applied to this type of comparison, such as maintaining the integrity of the number and distribution of IFC entities and their globally unique IDs between the two IFC files. It should be expected that there are the same number and type of building elements; however, it can never be guaranteed that the two IFC files will be identical in all respects. With either type of test there are two mappings between the IFC file and the internal CAD representation of the model during which information can be modified, deleted, or improperly mapped. These information changes might not be expected or acceptable.

3.1. IFC certification process

The IFC certification process [18], from 2007, was used to certify IFC compliant applications and was run by buildingSMART [19], formerly known as the International Alliance for Interoperability (IAI), the organization that oversees the development and implementation of IFCs. Certification was based on importing and exporting a set of IFC files with the application being certified. The certification was for a specific version of IFC, IFC2x3, and for a specific subset of IFC known as a view definition. The only view definition that was certified was the extended coordination view [20] which is used for coordinating the architectural, building service and structural disciplines during the design phase of a construction project. This includes:

- the spatial structure of the building,
- information about the building elements,
- logical relationship between elements and spaces,
- 3D geometry for clash detection,
- 2D/3D visual design intentions (color, hatching, rendering), and
- property information of building elements.

Other model view definitions [21] are being or have been developed for quantity takeoff, energy analysis [22], precast concrete design and detailing [23], and basic facilities management handover [24]. A new IFC certification process is also being developed that includes an online certification testing service for IFC files [25,26].

The IFC files used in the certification process are divided into two categories known as Step 1 and Step 2. The Step 1 IFC certification files for the extended coordination view are a large set of small models dealing with: building elements (walls, beams, columns, slabs, doors, windows, stairs, ramps, railings, roofs, curtain walls, members, plates, piles, footings, and spaces); building services elements (energy conversion devices, flow controllers, fittings, segments, terminals, air handling units, piping, heating, cooling, ventilation, and electrical systems); and annotation elements (lines, hatching, text, surfaces, material, and grid). Individual building elements are divided into subcategories such as beam profiles, beam axis, beams with clipping geometry, beams with boundary representation geometry, beams with mapped items, and beams with openings. Similar subcategories exist for the other building elements. Most of the Step 1 IFC files are less than 1 Mb in size and only contain a few building elements or other features. The Step 2 certification files are two or three large models of real structures that contain most of the elements from the Step 1 files.

The results of exchanging each of the IFC files between the CAD applications being certified are documented in spreadsheets including: a short description of the test model, version of the originating CAD application and IFC exporter, a screenshot of the model, and comments about geometry as imported to the other CAD applications and IFC viewers. After all issues are resolved with the exchanges then the application is certified.

There has been a lot of discussion about the problems with the IFC certification process. The major problem is that user expectations are not being met by CAD applications, which have been granted IFC certification and should be able to exchange 100% of the information in their CAD models via IFCs 100% of the time [27–29]. They are usually unaware that the certification is only for the extended coordination view and that the testing process does not ensure that exchanging IFC for real projects will always work. The certification process was more of a test of the ability to exchange information via IFCs rather than the quality of the exchange. Although these issues are very important for the continued development, implementation, and use of IFCs, these issues and ways to improve the process are outside the scope of this paper and are being addressed by buildingSMART.

3.2. Danish IAI IFC exchange test

One of the first documented interoperability tests, outside of the IFC certification process, was carried out by the Danish chapter of the IAI in 2006 [30]. This test modeled a simple structure in five CAD applications, exported the model to an IFC file (version 2x or 2x2 depending on which was supported in the CAD application), and imported the IFC file to the other four CAD applications. The structure contains four composite walls (concrete, brick, and insulation), a slab floor, spaces defined by the walls and floor, and openings in one of the walls for a door and window as shown in Fig. 2. The criteria for evaluating the exported IFC files were: (1) the accuracy of the geometry including the openings, (2) object types, (3) the composition of the wall, (4) relationships between the components (walls, openings for the door and window), and (5) properties such as name and material type of the building elements. After the IFC files were imported to the other CAD applications, the same criteria were used to evaluate the resulting model in those applications. The evaluation results indicate if a particular criterion is applicable, if the criterion was passed, and if not, why it failed. The test documentation includes some of the procedures that are needed in the CAD applications so that IFC information is correctly exported and imported. The test also indicates which version of IFC is used for a particular exchange between two CAD applications and the version numbers of the CAD software and IFC interface.

3.3. Precast concrete data interoperability benchmark test

The precast concrete data interoperability benchmark test was part of a larger project related to Building Information Modeling for Precast Concrete [31,32]. The first part of the project was an experiment in which a precast concrete building was modeled and exchanged using BIM software concurrently with its actual design and fabrication detailing of its precast parts using traditional 2D CAD tools. The last part of the project defined the information exchanges needed for the design and fabrication of precast architectural facade pieces.

The second part of the project was the interoperability benchmark test. The test models a well-defined mostly precast concrete structure

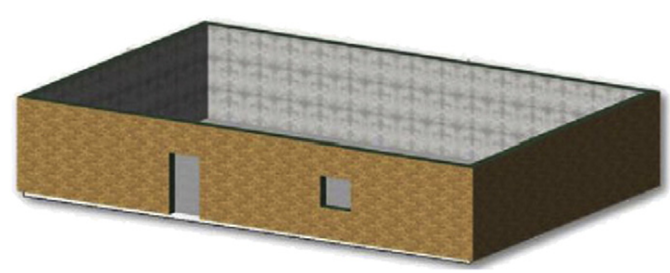

Fig. 2. Simple structure used for IFC exchange test [30].

in four CAD applications, exports an IFC file, and imports it into one CAD application to do more detailed design of rebars and connections. Interoperability between the CAD applications was also tested with DWG drawing files and SAT solid model data format files. The benchmark test model shown in Fig. 3 contains three different types of members: (1) reinforced cast-in-place concrete members such as columns, slabs, and footings; (2) steel members such as columns, beams, and bracing; and (3) precast concrete members such as beams, hollow-core slabs, and architectural façade panels. The modeling of the structure was broken down into specific units such as a concrete column and footing, a precast panel, or a wall with circular and rectangular holes. A description of the modeling procedure for each unit is defined along with its native object type (wall, column, beam, slab, floor, etc.).

After the benchmark test model was created in four CAD applications, an IFC file was exported from each. The IFC files were then imported back into their originating applications and the resulting model was evaluated. The evaluation consisted of checking if the geometry was correct for each object type and to note any problems. For one of the CAD applications that could not import an IFC file, the exported IFC file was checked in an IFC viewer.

The exported IFC files were also evaluated by two other criteria: the number and type of IFC entities used to model the native objects and the size of the IFC files. The first criteria showed widely differing total and individual entity type counts between the CAD applications. The IFC files sizes were similar except for one application. The differences in the entity counts are attributed to how the internal representation of native objects in the CAD applications (wall, column, beam, and floor) are mapped to IFC entities (IfcBeam, IfcColumn, IfcWall, IfcBuildingElementProxy, etc.) and how geometry (extrusions or boundary representation) is represented in the IFC file.

The next step involved importing the IFC file, from the original four CAD applications, into a different CAD application for the purposes of doing a more detailed design of rebars and connections. The resulting four models in the receiving CAD application were evaluated for correctness of the geometry and attributes such as profile names. The geometry, position, and orientation were checked for each individual unit and subunit. For example, an individual unit might be the back side concrete wall while a subunit might be the relief on a façade panel. Each test criterion applied to a unit or subunit either passed or failed and a total score was given for each IFC import. Overall conclusions were reported based on the exchange of geometry and the exchange of semantically meaningful information regarding how elements for precast architectural facades are modeled and mapped to IFCs.

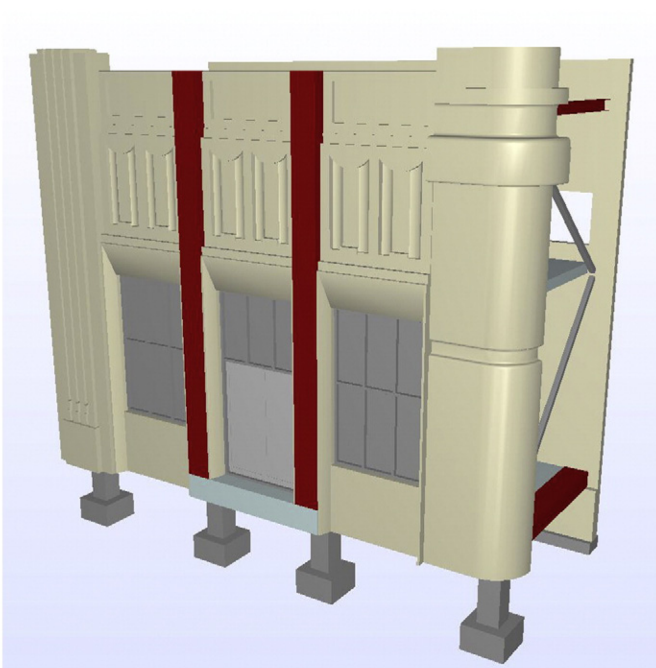

Fig. 3. Precast concrete data interoperability benchmark test model.

3.4. ATC-75 project: development of industry foundation classes for structural components

The purpose of the ATC-75 project is the further the development of IFCs for structural components [33]. The primary information exchange use case is between an architectural model and a structural model. Interoperability testing is a major part of the project in terms of: (1) identifying the problems in exchanging IFC files from an end-users perspective; (2) defining a prioritized set of attributes related to objects (columns, beams, braces, walls, slabs, footings, grids, stories) to address the problems; and (3) recommendations for current IFC implementations and future IFC development.

The benchmark test model is a section of a sports stadium, shown in Fig. 4, that has been modified from the original design and additional element types have been added. The model was generated in three CAD applications, exported to IFC, and imported into each of the other applications. The test model is made up of the following object types: columns, beams, braces, walls, and slabs. For each object type, several specific instances were selected and the details of their attributes such as position, profile name, material type, material grade, length, and roll were documented. The documentation includes screenshots of each specific element and its properties and a table of the detailed properties. A table of the types and ranges of expected values for each attribute of each attribute was also developed. From each CAD application an IFC file was exported that was verified by checking the: (1) file header; (2) file syntax and conformance to the IFC schema; (3) basic information such as units used; and (4) visual appearance of the model in an IFC viewer and attributes of the model that could be accessed in the viewer.

Then the IFC files from the three CAD applications were imported into each other and the results documented. The documentation includes a check of the overall geometry and the exact geometry and attributes of the specific instances described above. The geometry and attribute evaluations also include screenshots from the CAD application of the instances of the specific objects and their properties.

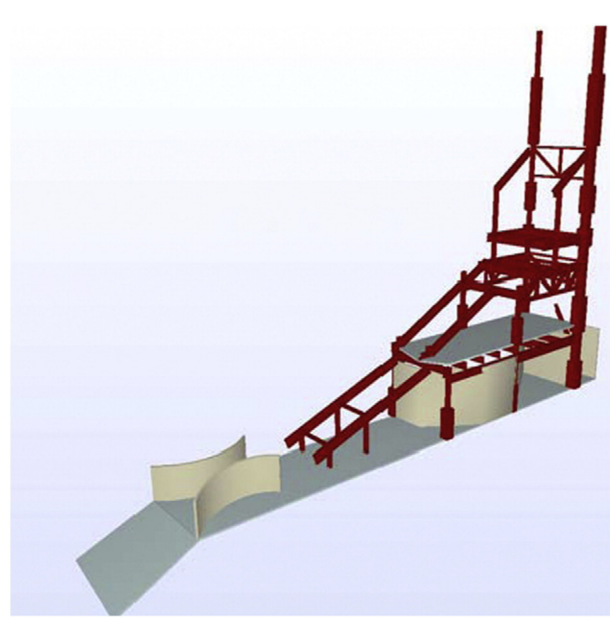

Fig. 4. ATC-75 project stadium benchmark test model.

3.5. Re-export test at FZK

The re-export test was an informal benchmark test carried out at the Forschungszentrum Karlsruhe [34] in 2008. The test involved exporting an IFC file of a simple structure, shown in Fig. 5, from one CAD application, importing the IFC file to seven CAD applications (including the originating application), and then "re-exporting" another IFC file from the seven applications. The structure is a house including rectangular and circular windows, two types of doors, several rooms, furniture, bathroom fixtures, and a spiral staircase. The test involved comparing the seven re-exported IFC files to the original IFC file.

Several criteria were used to compare the original IFC file with the seven re-exported IFC files. Those criteria for comparison include: (1) the visualization of the model in the CAD applications and other IFC viewers; (2) general information such as the file size, entity count, types of entities, syntax and semantic checking, and owner history; (3) distribution of IFC entities and relationships; (4) maintaining the same IFC globally unique identifiers (GUID) for specific entities; and (5) maintaining the name attribute for specific entities. For each of the criteria, the values were documented in spreadsheets and noted if they were different from the values in the original IFC file. The results of the test were posted only on a discussion forum for IFC software developers.

3.6. Geometric data exchange

The research for this IFC benchmark test took place at the University of Ljubljana in Slovenia in 2005 [35]. The test procedure is similar to the re-export test described above. Two simple structures (wall and wall with openings) were modeled in three CAD applications, exported to IFC, imported back into the same three CAD, and re-exported again to an IFC file. The re-exported IFC files were then compared to the original IFC files. Four models of more complex structures with hundreds or thousands of building elements (houses and office buildings) were obtained for two of the CAD applications. The re-export test procedure was also applied to those models.

The criteria used for comparing the original with the re-exported IFC files include: (1) visualization with IFC viewers; (2) general information such as the file size, entity count, types of entities, and syntax checking; (3) differences in shape representations; (4) use of property sets; (5) maintaining the same IFC GUID and specific attributes related to doors and windows. For the complex structures other criteria include: (1) alignment of building elements; (2) changes in geometry; and (3) improper mapping of building elements. For both the simple and complex structures the comparison of IFC files was mainly done by manual inspection. Software tools such as IFC viewers and entity counters were also used. Finally, the research provides a detailed explanation of some of the causes of the differences between the IFC files and suggestions to improve comparisons between IFC files.

3.7. Automated comparison of IFC Files

At least two research projects have developed methods to automatic comparison of one IFC file to another. Each has their own criteria for evaluating the differences. The first project developed a software tool, known as EVASYS, which automatically evaluates the similarities and differences between two IFC files [36]. The software works by first matching object types, then matching object instances by using the GUID, and finally comparing the attributes for matching instances. The software was used to test sets of IFC files that have been "roundtripped" as described in Section 3 above. The imported and exported IFC files were analyzed by EVASYS. The test IFC files were a mix of files from other demonstrations and exemplar building models from CAD applications. EVASYS reported inconsistent values and entities in only the original or roundtripped IFC file. Subsequent testing with EVASYS used a subset of the IFC Step 1 certification files. Those files covered objects such as beams, columns, walls, doors, railings, roofs, slabs, and windows with various geometric representations and other features [37].

The second project has developed a method to generate oriented graphs from an IFC file [38]. Graphs from different IFC files can be compared and the differences in the graph nodes (no change, match but contents have changed, removed, or added) are quantified. The focus of the research was more on developing the method of comparing IFC files rather than the results of the comparison.

3.8. NIST column test

A simple IFC interoperability test was performed at NIST by modeling a single steel column with an I-shape cross section in five CAD applications, exporting it to IFC, and importing it to the other CAD applications. The criteria used to check the resulting model include: (1) accuracy of the geometry; (2) object, family, style, or group type; (3) geometry representation used; (4) ability to edit the resulting geometry; (5) maintaining element properties; (6) where attributes

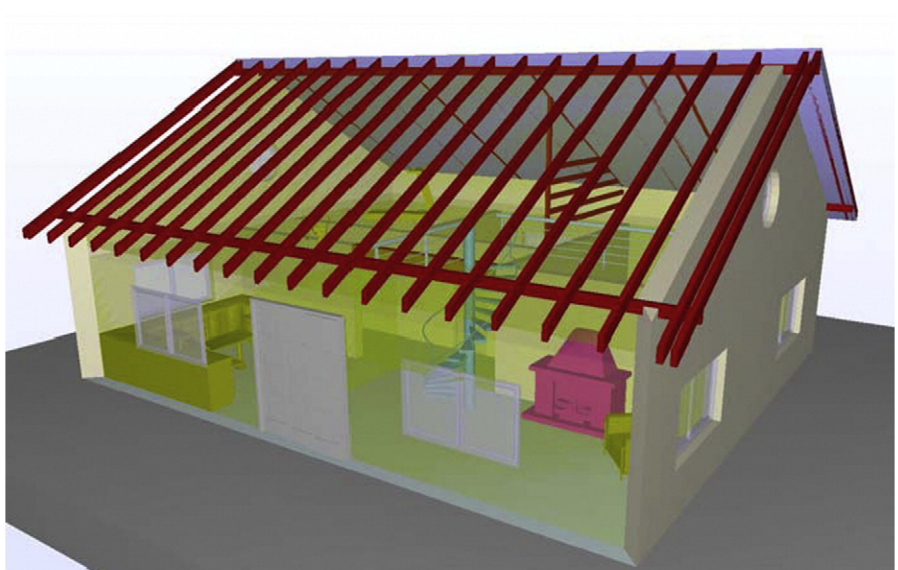

Fig. 5. Re-export test model (part of the front wall and roof are removed).

of the column, such as a user-defined name or profile name, appear in the IFC file; and (7) how and where information about the column is accessed in the receiving CAD application. The resulting IFC files were evaluated with similar criteria.

3.9. Summary of tests

The preceding tests are summarized in Table 1. Each test is classified by the starting point of the test (a generated or existing CAD model) and the test criteria (if the CAD model or IFC is evaluated and at what point in the workflow). The numbers associated with each test in the column headings refer to the sections above. In the table, the first row of Test Criteria "Compare original CAD model to resulting CAD model after IFC file import" generally refers to postprocessor testing and the second row "Evaluation of exported, re-exported, or roundtripped IFC file" refers to preprocessor testing.

4. Non-IFC interoperability projects

Several other non-IFC product model exchange and interoperability initiatives have benefitted from rigorous conformance and interoperability testing programs. Some of the lessons learned from testing these product models could be applied to IFC conformance and interoperability testing programs. Three of the testing programs are detailed in this section.

4.1. AP 227 — plant spatial configuration

Part 227 of the ISO 10303, Application Protocol: Plant Spatial Configuration (known as STEP AP 227) is an international standard for the exchange of spatial configuration information and functional information of process plants [39]. The scope of an application protocol is defined by the type of product, the supported life cycle stages of the product, participating disciplines and the required types, and uses of product data. An application protocol also defines the conformance requirements organized in conformance classes for conformance testing of implementations.

The elements of this protocol include shape representation, spatial relationships between elements, piping system design and fabrication information, and functional information for piping and HVAC (heating, ventilation, and air-conditioning) systems. Included with the development of the application protocol was the validation that the application protocol specification covered all requirements and provided a consistent and deployable solution.

An ISO 10303 application protocol includes [40,41]:

- Application Activity Model (AAM) — a process model that describes the activities and processes that use and produce product data. The AAM also documents specific tasks or usage scenarios that must be supported. The AAM is similar to an Information Delivery Manual (IDM) process map that is used to define the exchange requirements for domains related to IFC [42].

Table 1
Summary of IFC interoperability benchmark tests.

		IFC Certification Process (3.1)	Danish IAI IFC Exchange (3.2)	BIM for Precast Concrete (3.3)	ATC-75 Structural IFC (3.4)	Re-Exportfrom FZK (3.5)	Geometric Data Exchange (3.6)	Automated Comparison (3.7)	NIST Column (3.8)
Test Type		Many-to-many	Many-to-many	Many-to-one and roundtripped	Many-to-many	One-to-many (re-export)	Many-to-many (re-export)	One-to-self (Roundtrip)	Many-to-many
Test Starts With	CAD model generated from input specification	For Step 1 certification, many categories and subcategories of building elements	Simple structure with walls, slab, openings, wall composition	Wall, column, beam, slab, floor elements consisting of reinforced cast-in-place concrete, precast concrete, steel members; documented modeling procedure			Single wall with and without door and window openings		Single steel column with I profile
	Existing CAD model	For Step 2 certification, complex buildings from each CAD application			Segment of stadium with modifications; details about specific elements	House with windows, doors, furniture, bathroom fixtures, staircase	Two houses and two office buildings	Example buildings and IFC files from other demonstrations	
Test Criteria	Compare original CAD model to resulting CAD model after IFC file import	Geometry, position, some properties	Geometry, position, object type, wall composition, element relationships, properties	Geometry, position, object type, name attributes, properties, editable geometry	Geometry, position, element attributes and properties	Geometry			Geometry, editable geometry
	Evaluation of exported, re-exported, or roundtripped IFC file	Geometry, syntax check		File size, entity count and distribution, object mapping, shape representation		File size, entity count and distribution, relationships, syntax checking, owner history, GUID	File size, entity count and distribution, syntax checking, object mapping, GUID, attributes		Entity count and distribution, object mapping, shape representation, attributes, properties
	Compare original IFC file to re-exported or roundtripped IFC file					Comparison using the criteria above	Comparison using the criteria above	File size, entity count and distribution, automatic matching of entities between files	Comparison using the criteria above

• Application Reference Model (ARM) — a model that specifies the conceptual structures and constraints used to describe the information requirements. The ARM is similar to the exchange requirements of an IDM.
• Application Interpreted Model (AIM) — a model of selected data structure resources which are constrained, specialized, or completed to satisfy the information requirements of the ARM. The AIM is similar to a Model View Definition (MVD) that specifies the IFC entities and values required to satisfy a particular exchange requirement.
• Conformance Requirements — the list of the requirements which software implementations shall satisfy. These are organized into conformance classes for specifying different levels of compliance for software implementations.

An application protocol validation report documents the successful assessment of completeness and correctness of each component and the integrity of the set of components for specifying the needed data exchange capabilities. The AP 227 Validation Report also documents a pilot demonstration of AP 227 and the details on the information exchanges between different participants such as equipment vendors, owner/operators, contractors, and fabricators for the purpose of doing conceptual through detailed design. The information exchange requirements are defined between each participant. At the core of the demonstration is the set of test data that is exchanged in the ISO 10303 Part 21 neutral text file format. The project tested whether the software applications could process and use the data in the AP 227 files, understand how to retrieve the information, and test if the file information required was correct and adequate for the specified usage scenarios.

Detailed test models were developed for part of a process plant. The test model was broken down into smaller well-defined units which when combined made up the complete process area of a process plant model. For example, one of the testing units is of a simple 3D piping arrangement in Fig. 6. The exact dimensions of every pipe, valve, pump, flange, nozzle, tank, weld, insulation, and plate are specified. Other model units include other equipment, complex piping, mechanical, electrical, HVAC, and structural components.

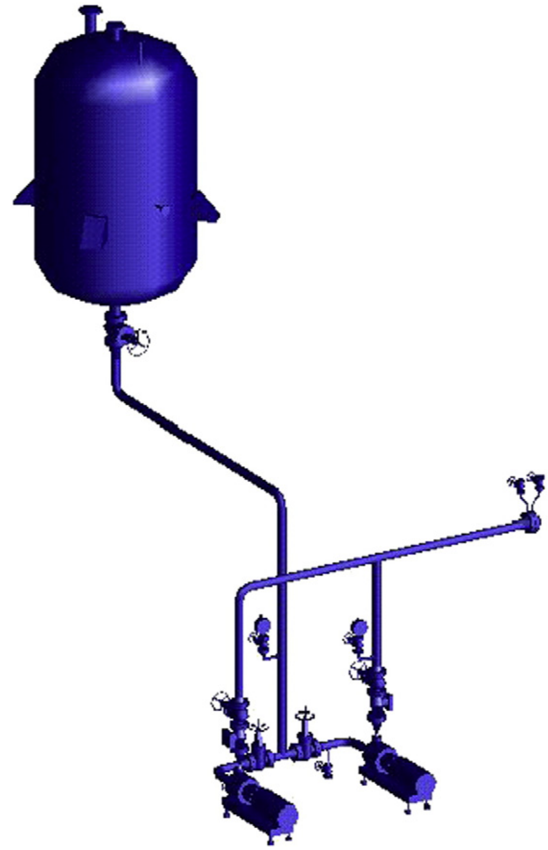

Fig. 6. AP 227 3D piping arrangement test model [39].

The shipbuilding industry reviewed the first release of AP 227 and determined that it provided much of the functionality needed for the exchange of ship piping and HVAC system models. The Navy/Industry Digital Data Exchange Standards Committee (NIDDESC) developed industry consensus on product data requirements and worked to ensure these industry requirements are incorporated into national and international data exchange standards. NIDDESC developed an AP 227 test suite and a usage guide which were used to improve the AP 227 software interfaces for selected applications and as baseline test suites for demonstration projects. Leaders in the shipbuilding industry and several navies promoted the use of AP 227 in new shipbuilding contracts but critical mass for supporting broad commercialization of the use of AP 227 across applications for the design of ships and ship systems was not achieved.

During the development and pilot implementations of AP 227, participants documented the challenges and limitation of the STEP architecture and the original concepts of abstract test suites [43]. An abstract test suite defines test cases and criteria to measure conformance (known as verdict criteria) independent of specifying the product data exchange format being implemented or values for a specific test case. This is intended to allow the same abstract test suite to be used for different product data exchange formats and potentially as scripts for automated testing and thus enabling more cost effective testing. The application of the abstract test suite principles to the realities of building and managing executable test suites and testing programs for the complexity of industrial product modeling software demonstrated many limitations. The greatest challenge was the lack of tools to automatically generate test files and test scripts from the abstract test suite. Without such tools, developing the test files from the abstract test suite required significant human labor with no obvious benefit over just building the test files directly without the abstract test suite. Although the ISO 10303 project had proposed developing specifications for multiple implementation formats, only one implementation format (ISO 10303 Part 21 neutral text file format) was adopted by industry. This removed the potential benefit of using the abstract test suite for developing test suites for alternative implementation formats.

4.2. AP 203 — mechanical parts and assemblies

Although the aerospace and automotive industries made significant investments in developing STEP and the subsequent application protocols, only a few have achieved traction and are included as interfaces in commercial CAD packages. AP 203, Configuration Controlled 3D Designs of Mechanical Parts and Assemblies, is the most prevalent example [44]. Industry consortia which have invested in the development and deployment of AP 203 have developed test suites to cover most of the standard, the types of complexities often encountered and major enhancements to the standard.

Although there is no formal certification process for assessing implementations of AP 203, the CAx Implementor Forum [45] defines best practices for translator implementations and 24 test suites that test multiple aspects of conformance and interoperability of CAD software implementations that use AP 203. Fig. 7 shows a mechanical part from one of the test suites. Each test suite presents the definition of several real or synthetic test cases, the motivation for the test, how the models are to be constructed, and how they are to be tested. During each round of testing the test cases are: (1) modeled in several CAD systems; (2) translated to a STEP Part 21 file; (3) and checked for syntax, structure, and semantics via a web-based testing system. Once

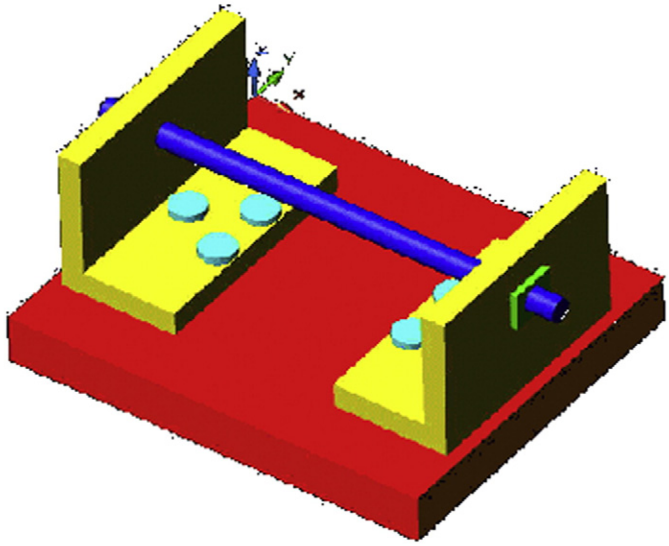

Fig. 7. CAx Implementor Forum test model [45].

the file passes these criteria it is made available for import to other CAD systems and various diagnostics are run to assess the semantic validity and functional quality of the imported information. At the end of each round of testing, the testing participants meet to resolve any issues related to the data exchange and standard.

4.3. CIS/2 — CIMsteel Integration Standards

CIS/2 is the product data model and file exchange format used by the structural steel software systems to exchange design, analysis, detailing, and fabrication information. STEP is the technical basis for CIS/2 similar to IFC and it uses the same resources to describe geometry.

Concurrent with the development of the standard, conformance requirements were created that specify what software vendors are required to do when developing CIS/2-conformant systems and how to make them CIS/2-conformant. The requirements are documented in volume 5 of the standard. Hundreds of conformance classes were developed that represent valid testable subsets of the CIS/2 schema. The conformance classes, individually or in combinations, are used during conformance testing. They also describe what has been implemented for a particular CIS/2 translator. The previous version of CIS/2, known as CIS/1, also defined conformance requirements and testing protocols [46].

Requirements and details for doing different types of conformance testing are also defined along with hundreds of abstract test cases that can be used to test CIS/2 implementations for conformance. The abstract test cases only test the syntax of individual concepts of how information is represented in CIS/2 and do not necessarily reflect real steel structures.

However, in practice, very few software implementations use the conformance classes or abstract test cases to test conformance to CIS/2. The initial set of software systems that implemented CIS/2 did use the conformance classes and tested their CIS/2 import and export capabilities by exchanging CIS/2 files of real structures; however, there was no formal certification of the implementations. Some representative sample CIS/2 files from each application were tested for conformance with commercial testing tools and the results were reported on the Georgia Tech CIS/2 website [47]. Currently, there is no organization that enforces any type of conformance or interoperability testing for CIS/2. Without that there can be no certification process. Any testing that does take place is only informally between two software vendors to test that a particular data exchange works between their software systems.

5. Assessment

The summary of the IFC and non-IFC interoperability projects shows a wide variety of testing methodologies and criteria used to evaluate the success of the data exchanges. Most of the projects include some aspects of interoperability testing where the original and resulting CAD models are compared to each other. However, there is a large range of criteria used for the comparison of the CAD models. Some only do a visual check of the model (Re-export test, Section 3.5) while others are much more rigorous (Precast Concrete 3.3, ATC-75 3.4, Danish IAI IFC Exchange 3.2) in looking at other criteria such as attributes and properties of building elements. The IFC certification files for Step 2 are so large and complex that a thorough evaluation of interoperability is not really possible other than a visual check and a closer inspection of a few select elements. In contrast, the models used for the Precast Concrete interoperability testing are very well-defined and the differences in the model in the receiving CAD system are well-documented. Regardless, any type of interoperability testing requires a detailed checklist of test criteria to evaluate the resulting CAD model. More automated interoperability testing to compare information in the original CAD model with the resulting CAD would be a vast improvement over what is now mostly a manual process.

Aspects of conformance testing, such as checking the syntax and structure of the IFC files with free or commercial IFC file checkers testing, are found in some of the interoperability projects. There is also usually a visual check of the geometry in the IFC file but this is less useful as the size of the model increases. A more systematic check of the semantics requires inspection of all the building elements, their attributes and properties, and relationships to other building elements which currently is not an automated process.

Other types of test criteria that have been used do not necessarily fall under the strict definitions of conformance and interoperability testing. The most common of these tests is to make a comparison of one IFC file to another. For projects that relied on re-exporting or roundtripping an IFC file (Re-export 3.5, Geometric Data Exchange 3.6, Automated Comparison 3.7), comparing the original to the re-exported or roundtripped IFC files was the primary test methodology. Comparing IFC files is much easier than comparing CAD models, as would be required by interoperability testing, because there are many characteristics of an IFC file that can simply be counted and measured. Those measures included file size, entity count, types of entities used, and types of attributes assigned to objects. However, any differences found between files are more likely an indication of how internal CAD representations are mapped to and from IFC files. Comparing one IFC file to another does not fit any definition of conformance, interoperability, preprocessor, or postprocessor testing and does not involve checking the files against the IFC schema. The point of data exchange with IFC files is to exchange information between CAD systems in a real environment which requires a comparison between the original and resulting CAD models and not necessarily the IFC files.

On the other hand, some of the comparison of IFC files did show some interesting results. With the Precast Concrete interoperability project, the same precast concrete structure was modeled in four CAD systems and exported to IFC. The four different IFC files showed a wide variation in the total number of building element entities and the distribution of types of building elements used such as beams, columns, slabs, footings, etc. The variations indicate either (1) the differences of how similar objects in each CAD system are modeled and mapped differently to an IFC file or (2) the differences in how similar objects were modeled by different users. These differences can provide insight as to why CAD systems may or may not be able to interoperate with those IFC files. However, comparison of the IFC files to each is not a measure of conformance to the IFC schema.

One area where comparing IFC files could be used for conformance testing is to have reference IFC files. IFC files generated by CAD systems would be compared to reference IFC files that are generated and certified for their correctness by a standards body. The comparison between the CAD generated IFC file and reference IFC file would have to take into account what part of the IFC file is being tested for conformance and any vendor-specific issues related to the IFC file. The benefit of this type of comparison is that while there are existing tools for testing the syntax and structure of an IFC file, the comparison could test the semantics of an IFC file. Some of the existing tools such as EVASYS and others being developed, such as Compare21 [48,49], could be adapted to automate this type of comparison.

One of the primary tests used in the interoperability projects is to visualize the geometry in an IFC file with any of several free IFC viewers. These viewers also provide the capability to drill down to individual property and attribute values associated with a single building element. However, this method of inspecting values is useful for only small IFC models. The NIST IFC File Analyzer [50] converts an IFC file into a spreadsheet where each worksheet contains all the values associated with one type of entity. Being able to scroll through all the values associated with a particular building element type is a great improvement for the manual inspection of values, properties, and attributes in an IFC file.

Most of the interoperability projects used a small well-defined CAD model or IFC file to test. However, the IFC certification process uses hundreds of IFC files for testing. In either case, it would be useful to know how much of the IFC specification is covered by an individual file or set of files. Coverage analysis is an important aspect of conformance and interoperability testing as defined by Kindrick et al. [11]. Without doing a coverage analysis of a set of IFC files, the true measure of conformance or interoperability cannot be determined. Coverage analysis can be done based on varying concepts, such as: types of geometry, use of optional values, a model view definition, or a particular domain or extension to the IFC specification. A complementary problem is how a meaningful set of IFC files can be automatically generated to ensure coverage of a particular concept. This would ensure that when conformance and interoperability testing is performed with a set of IFC files, for which the coverage is known, an accurate measure of the test results can be reported.

Falsification testing is commonly used to test software systems for conformance [51]. Falsification testing can only prove that a software system is not conformant. IFC files could be constructed that purposely have invalid data. When invalid IFC files are imported to a CAD application, the software should indicate an error. Applications that do not process invalid data correctly might be considered non-conformant.

There is a great need for well-documented, reliable, repeatable, and meaningful testing methodologies for conformance and interoperability for product data exchange specifications. All of the interoperability projects are snapshots at the time of the testing of the state of conformance or interoperability with particular versions of CAD software and IFC interfaces. Most likely, the software and interfaces have been upgraded since the interoperability projects were first performed. Repeating the testing could show improvements in conformance and interoperability, however, more useful results might be obtained if there were better testing methodologies. The development of better testing methodologies also has to be balanced with the realities of the time and cost of doing testing and who is performing the testing whether it is a conformance testing service, the software developer, or end-user. The most thorough and robust testing methodology might be infeasible to implement, and tradeoffs will have to be considered to ensure that the conformance and interoperability testing are cost effective and not an excessive burden.

6. Conclusions

The assessment of different initiatives and methods for conformance and interoperability testing illustrates the strengths and limitations of each and clarifies the principles and procedures that have proven to be most effective for testing implementations of construction product data exchange standards. At present, there are no common, proven methods and rules for defining the structure, granularity and verdict criteria of a test suite for construction product data exchange standards. Tools are available for checking the syntax and structure of test files, but the process for assessing semantics requires significant human involvement and can make conformance and interoperability testing prohibitively expensive.

For improvements in the use of conformance and interoperability testing, that are necessary for delivering effective PDE specifications and establishing end-users confidence in software implementations for automated data exchange, industry and research organizations should:

- develop a common methodology for conformance and interoperability testing which includes (1) the generation of well-defined test models that include the relevant characteristics of the information exchange requirements being tested, and (2) robust test criteria that are used to evaluate the syntax, structure, and semantics of test files and the results of importing them to applications;
- develop methods to generate test files and test criteria based on model view definitions that can provide the basis to meet the testing requirements of a particular domain;
- use coverage analysis based on criteria such as model view definitions to ensure that optimal sets of test files is used for conformance and interoperability testing;
- develop methods and tools for automating conformance and interoperability testing particularly for postprocessor testing of semantics.

Much of the construction industry is starting to understand the importance of conformance and interoperability testing in order to achieve integrated and automated work processes, with savings in cost and time. Additional research, development and pilot demonstrations are needed to prove and deliver cost-effective conformance and interoperability testing in conjunction with evolving standards like IFC and CIS/2. As more sectors and disciplines of the construction industry adopt building information modeling and integrated design and delivery work processes, there will be increasing pressure to deliver software products with viable increments of interoperability. Without such advancements, the construction industry will continue to be hindered by incomplete interoperability with open-standard product data exchange specifications.

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